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ADVANCED LIFE ASSESSMENT METHODS FOR GAS TURBINE ENGINE COMPONENTS

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Abstract

In combustion systems for aircraft applications, liners represent an interesting challenge from the engineering point of view regarding the state of stress, including high temperatures (up to 1500°C) varying over time, high thermal gradients, creep related phenomena, mechanical fatigue and vibrations.
As a matter of fact, under the imposed thermo-mechanical loading conditions, some sections of the liner can creep; the consequent residual stresses at low temperatures can cause plastic deformations. For these reasons, during engine operations, the material behaviour can be hardly non-linear and the simulation results to be time expensive.
Aim of this paper is to select and implement some advanced material life assessment methods to gas turbine engine components such as combustor liners.
Uniaxial damage models for Low Cycle Fatigue (LCF), based on Coffin-Manson, Neu-Sehitoglu and Chaboche works, have been implemented in Matlab®. In particular, experimental LCF and TMF results for full size specimens are compared to calibrate these models and to assess TMF life of specimens. Results obtained in different testing conditions have been used for validation.
In particular, each model needs specific parameter calibrations to characterize the investigated materials; these parameters and their relation with temperature variation have been experimentally obtained by testing standard specimens.

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Keywords: **CREEP, MECHANICAL FATIGUE, DAMAGE MODELS, COMBUSTOR, AIRCRAFT ENGINE DESIGN**

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1. Introduction

European gas turbine industries improve continuously their technical skills in order to compete, to reach higher safety standards and also to meet future environmental standards.
The design requirements of new components should not compromise both safety and reliability.
To achieve this goal, a good knowledge is required of material behaviour and loading conditions with realistic and representative geometries.
The prediction of life and stress in the combustor is a very complex task, because the material, when subjected to high temperature cycles and residual stresses, can plasticize even at low temperatures.
Necessity arose in recent years to develop analytical models able to predict components life without large amounts of numerical simulation time expense.
Crack nucleation under cyclic loading has been investigated since many years, different models based on Basquin-Manson-Coffin laws [1] have been introduced for engineering practice, after wards many damage models [2-9] have been developed to estimate the life of the components, such as turbine blades [10], once they are subjected to different events, as variable temperature, creep and oxidation phenomena.
These models have been validated in several cases and materials: R. Minichmayr et al. [11] applied Sehitoglu's method on aluminium component; H. Mavoori et al. [12] studied creep and plastic deformation in Sn-Ag and Sn-Zn eutectic solders; V. Srikrishnan et al. [13] investigated the diffusion in transition metals and alloys; L. J. Cuddy et al. [14] proposed a method to evaluate the activation energy used in Sehitoglu's method; R.W. Lund [15] proposed another method to evaluate the activation energy for strengthened metals; Z. Y. Huanga et al. [16] described Chaboche's method applied on carbon-manganese steel; J. L. Chaboche [17] applied his method on advanced materials; R.P. Skelton [18] studied polycrystalline and single crystal nickel-base superalloys; the same R.P. Skelton [19] studied thermo-mechanical fatigue of a ferritic steel.
Other investigations have been performed in different experimental conditions: J. L. Chaboche [20] analysed the damage approach to the prediction on high temperature low-cycle fatigue; H. Kang et al. [21] proposed a model for variable temperature and loading amplitude conditions; and C.J. Hyde [22] investigated the failure mechanisms in high temperature materials subjected to isothermal and anisothermal fatigue and creep conditions.
The main aim of this work is to evaluate the performance of damage methods applied to super alloys in order to estimate the life for the combustion chambers in direct response to the requirements of the European community for reducing NOx produced by the gas turbine aircraft.
Although the objective of this work is addressed to the combustors of aircrafts, this technology is of general use, providing a good technique for the design and for the in-service support for all components of gas turbines subjected to creep phenomena and plasticity during each engine cycle.
In particular, basing wide investigation of literature, three predictive LCF damage models have been selected to estimate the material life: Manson-Coffin [1], Sehitoglu [2,3]and Chaboche [5,6].
These models have been implemented in Matlab environment; they have been calibrated and validated by means of isothermal tests on a NiT super alloy. These tests have been carried out on standard specimens in the Laboratory of the Department of Mechanical Engineering of the Politecnico di Torino.
The final aim of this research activity is to point out the method, which best fits the isothermal LCF behaviour of the super alloy.
Furthermore, the definition of an optimized calibration procedure, allowing to best estimate LCF high temperature life for different temperature levels with respect to those experimentally investigated, has been carried out.

2. Analytical model

The main mechanisms of Thermo Mechanical Fatigue (TMF) damage occurring in materials have been analysed; they can be divided into three main groups: Fatigue (plastic deformation), Oxidation (environmental impact) and Creep (temperature effect).

This investigation takes into account of other factors and in particular: maximum and minimum temperature levels, cycle time and residence time (for a load, at a set temperature), temperature-strain phasing.
Models available in literature can be divided into five groups: linear, non linear, cyclic, time-dependent parameters and temperature-dependent parameters. A further classification of the models is based by considering their

applicability.
General models (Manson-Coffin [1], Sehitoglu [2,3], Chaboche [4-7,10,17,20]) are based on physical mechanisms of crack nucleation and propagation. Their formulations are based on complex equations taking into account of constitutive material properties, but after calibration they are suitable for any loading history.
Empirical models (Skelton [9,18,19]) aim at direct application and are generally easier to use for engineering applications. They are based on energy criteria and their experimental calibration is immediate; after calibration, they are suitable for loading histories similar to those by means of which they are calibrated.
Each considered model is composed of three parts.
The first part is the basic law or constitutive law, and it describes the relationship between stress and strain of the material itself (elastic-plastic behaviour, viscoelastic, visco-elastic-plastic).
The second part refers to the damage model and it takes into account of the phenomena which cause damage in the material and how they work.
The third part defines failure criterion, that is the limiting expression of damage before failure occurs.
With reference to the superalloys, basing on the description of damage rules and its temporal evolution, the following models were analysed and implemented in Matlab: strain-range partitioning model I (Manson-Coffin); general damage model (Sehitoglu) and range partitioning model II (Chaboche).

3. Experimental setup

Material mechanical characterization has been obtained by means of standard mechanical testing: tensile monotonic, HCF in load control and LCF in strain control. All tests have been run at several temperature levels between 20° and 800°C. Creep tests results have been available from previous testing activities.
Static testing have been performed on a servo hydraulic Instron 8801 testing equipment, load cell Dynacell 2527 100 kN, hydraulic grips. Test speed has been set to 5 mm/min. At least three specimens have been tested at twelve temperature levels between 20 °C and 1000 °C.
HCF tests have been run on a Amsler vibrophore 10 HFP 422 testing machine. HCF tests stress ratio was set to R=0 due to elastic instability problems and the fatigue limit has been calculated by means of the Stair Case method [23]. Fatigue limit has been set for three levels of temperature: room, 500°C and 800°C. HCF tests have been run at about 110 Hz frequency. At least 15 specimens have been tested for each temperature level.
LCF strain controlled tests have been run on an Instron testing machine, 10 Hz loading frequency. LCF tests have been run with the following strain levels: 0.1, 0.3, 0.4, 0.6 and 1% total strain ε_t. At least three specimens have been tested for each strain level. These test have been run at room temperature, 300°C, 800°C and 950°C.
Creep stress controlled tests have been run at twelve temperature levels between 700 and 900°C.
Specimens have been laser cut from a 0.9 mm thick sheet, according to International Standards defining static and fatigue testing.
These data have been used to obtain the damage models parameter calibration as described in literature [1, 2, 3, 5, 6, 7, 8]. For example mean stress, strain and cycle to failure data obtained at the same strain and temperature level have been used to calibrate the two terms of the Manson Coffin model at a set temperature
Then for data obtained at different temperatures, a linear regression model has been calculated as a relation between the model parameters and the temperature. This way it is possible to estimate the parameters value for temperature values different from the tested ones. In particular the results obtained al 300 and 950°C have been used to calibrate the model and to simulate the LCF behaviour of the material at 800°C.
Sehitoglu and Chaboche models creep parameters have been obtained by processing also creep data.

4. Results and discussion

Due to confidentiality requirements, plotted results axes are hidden.
In figure 1, the tensile monotonic test results are plotted vs temperature. As it can be seen, high mechanical properties last up to 800°C and then decrease.
HCF test results showed that the fatigue limit obtained for the selected material decreases of about 30 MPa from 20°C to 800°C.
LCF tests data at 300 and 950°C have been used to calibrate the Manson-Coffin, Sehitoglu and Chaboche damage

models. In particular the models parameters (for example strain hardening coefficients and exponents) have been determined at the two mentioned different temperatures; then by means of a linear approximation of the parameters of the two temperatures the 800°C values of each parameters have been calculated. Then the 800°C experimental data have been used to validate the 800°C extrapolated models.

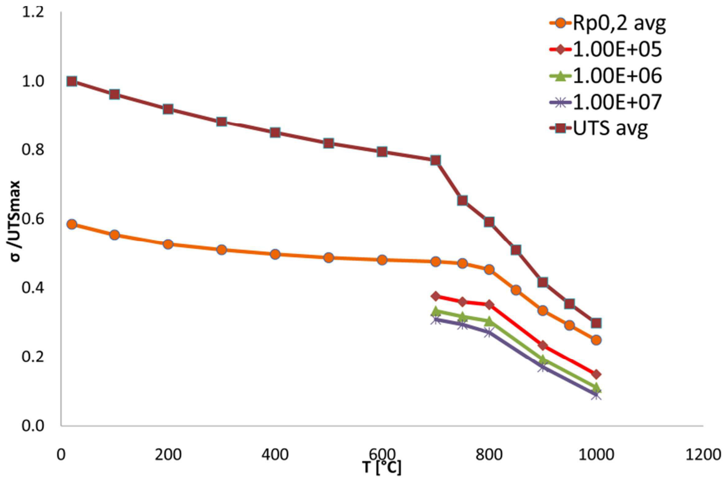

Figure 1: Monotonic tensile test results at different temperature and at specific stress cycles before failure (10^5, 10^6, 10^7 and 10^8).

In Figures 2 and 3 the experimental obtained damage models are plotted along with experimental calibration data obtained at 300° and 950°C for the examined damage models. In Figure 4 the life estimation curves obtained by means of linear interpolation of model parameters at different temperature are reported for 800°C. In the same plot experimental validation data of LCF 800°C tested specimen are reported. As it can be observed these models very well estimate experimental life for all the examined temperatures.
This means that the damage models well apply even for very high performance steels at elevated temperatures. In particular the Manson Coffin model, which requires a simpler calibration procedure, best estimates LCF high temperature isothermal life.
For the other models which require longer and more expensive testing procedures, the calibration is more difficult and the following research activity will investigate the performance of the more complex models in case of TMF lifing procedures.

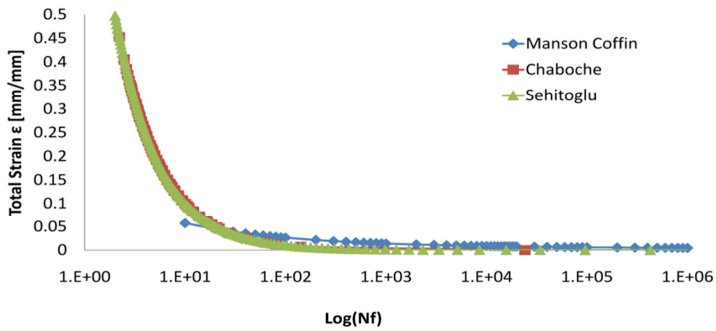

Figure 2: Damage models life estimation curves at 300°C.

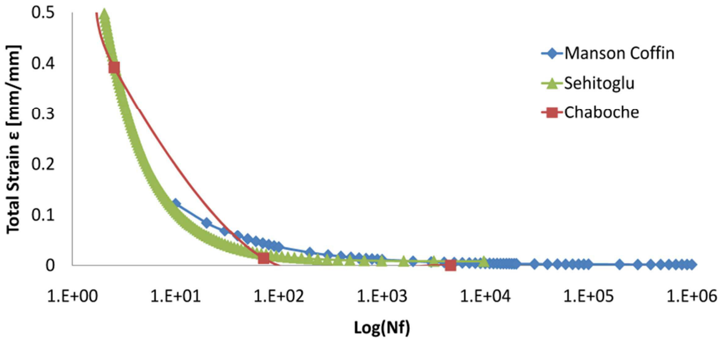

Figure 3: Damage models life estimation curves at 950°C.

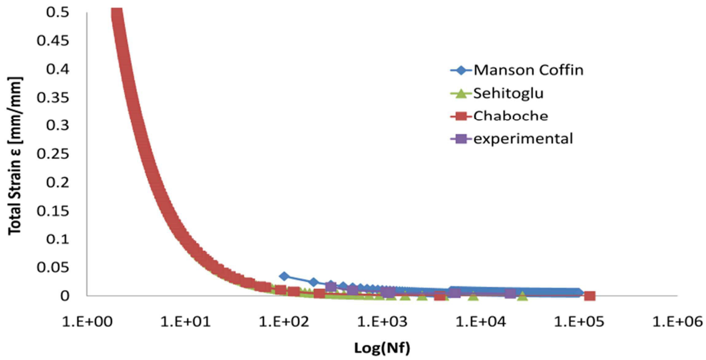

Figure 4: Damage models life estimation curves and experimental data, 800°C

5. Conclusion

Calibrated damage models allowed to estimate the life of LCF specimens in isothermal conditions.
In the present paper fatigue damage assessments based on Manson-Coffin, Sehitoglu, Chaboche models are applied to describe the LCF damage evolution. In particular, the investigation aims at evaluating which models best fits for the life and damage estimation for superalloys at high temperature levels.
The results showed that all the models well estimate experimental life of the material at high temperature levels and low and high number of cycles. Manson Coffin model better estimates LCF experimental life in isothermal conditions thus allowing to select this method for an optimized and economic calibration procedure. As a matter of fact the material behaviour at any high temperature isothermal conditions can be simulated by testing material in few temperature conditions. Further research activity will be dedicated to the estimation of TMF models performance for superalloys.

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